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# Analyzing Man-Made Vibrations, Diagnostics and Monitoring

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# Analyzing Man-Made Vibrations, Diagnostics and Monitoring

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SYNOPSIS: Machine foundation and construction vibrations are main industrial man-made vibrating sources. Eight presented case histories are divided on two groups: machine foundation oscillations and seismic effect of man-made vibrations. There is the attempt in this paper to suggest a guideline for determination the causes of arisen perceptible machine foundation vibrations. Some case histories are described shortly using the following set-up: arisen problem, field investigation and measurements, the suggested solution, the performance, and final results. Others case histories are elaborated in details.

## INTRODUCTION

Technical progress of industry is connected with intensification of man-made vibrations: making new equipment, increase in number of machinery and its capacities, extension of construction vibrations and in that number of blasting operations, increase of traffic vibrations.

In spite of the variety of industrial vibrating sources, machine foundations are the most wide spread man-made vibration sources. Abnormally high machine foundation oscillations are a serious disturbance for any enterprise. Therefore various aspects of analyzing, diagnostics and monitoring of these vibrations are important to prevent undesirable vibrating effect.

## 1. MACHINE-FOUNDATION-SOIL SYSTEM

The study of vibrating problems of machine foundations is an essential part in geotechnical engineering. The reliable design of machine foundations to accomplish trouble-free conditions is complicated problem. There are different methods for computing expecting foundation amplitudes, for example, Barcan (1962), Richart et al. (1970), Arya et al. (1979), Prakash and Puri (1988), Gazetas (1991). Some authors Aboul-Ella and Novak (1978), Srinivasulu and Lakshmanan (1978) have studied all components of machine-foundation-soil system. In many cases existing methods give acceptable results. However, in a number of other cases, design solutions are not satisfactory. The lack of information about dynamic loads transmitted from the machines to the foundations, certain approximation of the real physical system with used models, and still existing uncertainties in determination of dynamic soil properties make for the increase of foundation vibrations.

Often heightened foundation vibrations are impossible to predict using ordinary calculation methods prior to the machine have been installed and began to work since evaluation of vibration causes is beyond the possibilities of existing routine computation procedures. Nevertheless, available knowledge about the phenomena of machine foundation vibrations and corresponding experience gives a chance to analyze intolerable vibrations and make diagnostics of their appearance. After that it is very likely to decrease and stabilize these vibrations.

The most machines are mounted on rigid foundations. The machine, foundation and soil should be considered as the whole system which parts exert mutual influence on each other. When foundation vibrations are in tolerable limits, it means no problems for regular equipment use and no troubles for surrounding units.

For some reasons, foundation vibrations can exceed the allowable level becoming harmful for each part of the whole system. They cause excessive wear and bearing, cracking some machine parts and supply pipes, loose in fasteners, electric and electronic malfunctions in the equipment, damages of foundation structures and dangerous soil deformations. Also these vibration problems are important from an economic standpoint. The beginning of perceptible vibrations of machine foundations can occur in one or a few units of whole machine-foundation-soil system. It might have happened because of sharply increased dynamic loads transmitted from machine to foundation, foundation damage, or sudden changes of soil properties under the influence of vibrations and production process.

For elucidation of the causes existing vibrations of the system under consideration, it is necessary to consistently analyze each unit of the system. Examples of such analysis of the causes of intolerable machine foundation vibrations are shown in two case histories. Two more case histories demonstrate possibilities of decreasing foundation vibrations using machine vibroisolation and calculating the foundation with consideration of pulse duration.

### 1.1 Suddenly appeared high vibrations of a cone crusher foundation

Two cone fine crushers with the unbalanced horizontal force of 25 kN were used for reducing coal into fragments. Both of them were mounted on two separate identical concrete foundations consisting of walls, top and bottom slabs. The distance between crusher's axes was approximately 8 m. During long time, vibrations of crusher foundations were in tolerable limits, i.e. less than 0.3 mm.

All of a sudden, vibrations of one foundation increased and the displacement amplitude reached 1 mm. Such vibration level is dangerous for the machine and its foundation. The problem was to find the source of these vibrations. Changes in any part of whole machine-foundation-soil system can be the cause of arisen vibrations. Therefore a few logical steps were done in vibration analyzing for the diagnostics of vibration source.

The crusher. The unbalanced horizontal centrifugal force, horizontal and vertical impulse loads are transmitted from the operative crusher to its foundations. Impulse loads could not suddenly increased for regular and permanent technological conditions. The unbalanced force can only increase gradually in time. For these reasons the crusher as the source of new vibrations was excluded.

The crusher foundation. Observations of vibrating foundation exhibited that in spite of the large displacement amplitudes the foundation did not have any visible damage and cracks. It meant the foundation itself could not be the cause of arisen vibrations.

The soil. There were good soil strata under the crasher foundation: limestone with sandy and clayey interlayers. Usually no troubles appear about machine foundations underlain with soil like that. However, the crushing is a wet production process. Therefore it was assumed that water could penetrate under the crusher foundation and reversed soil properties. For this reason it was suggested to make a boring hole nearby. It proved that water did indeed turn weak soil underlayer into slash. After the water was pumped out, foundation vibrations returned back to the allowable limits.

## 1.2 Perceptible vibrations of the foundation under a powerful exhaust fan

A few powerful exhaust fans were placed at the enterprise for preparation of metallurgical raw materials. Fans were mounted on the same elevated pedestal foundations with columns' cross section area of 1 $m^2$. Perceptible foundation oscillations appeared during launching of one exhaust fan. In order to reduce these oscillations, the design company worked out a project to reinforce the foundation structures. Unfortunately, in a number of cases design engineers consider foundation reinforcement as the best remedy against high vibrations.

In diagnostic work it is necessary to look at the vibrating effect to try to find the cause. Therefore the observation of foundation structures and vibration measurements were made for two foundations with allowable and perceptible vibrations. Both foundation structures looked good with no damages and cracks, but the same machinery exerted different influence on those foundations. The comparison of acquired data permitted to conclude that the unbalanced exhaust fan was the cause of perceptible vibrations. After the fan was rebalanced foundation vibrations returned in the allowable limits.

## 1.3 Suspended vibrating isolation of cone crushers and decreasing dynamic loads on their foundations

Secondary and fine cone crushers are widely used for remaking of raw materials. Large horizontal unbalanced harmonic and impulse forces are transmitted to their foundations. Therefore these foundations are required substantial amount of concrete.

Vibrating isolation of the crushers gives the possibility of reducing excitation forces applied to the foundations to a marked degree and, in consequence of that, to considerably decrease the expenditure of concrete. Operating cone crusher speeds range from 200 to 400 rpm. Only special vibration isolators can be employed for such low frequencies. One of them is the suspended vibrating isolation which diminishes horizontal unbalanced force, applied to the foundation, up to 100 times and considerably reduces impulse forces.

Natural frequency of the isolated system, $\omega$, is calculated using formula for a mathematical pendulum

$$\omega = \sqrt{\frac{g}{l}} \qquad (1.3 - 1)$$

where g = Acceleration of gravity
l = Rope or rod length

Usually experimental frequency values are bigger the calculated ones. Analyzing of tested data reveals two reasons for increasing of measured frequencies: an existing slope of a rope (rod) line and an elastic pendulum hinge with constant angle stiffness. The influence of these causes can be assessed numerically.

### 1.3.1 An existing slope of the rope (rod) line

Consider the influence of an angle $\varphi_0$ on the values of natura frequency of horizontal system vibrations (Figure 1.3.1).

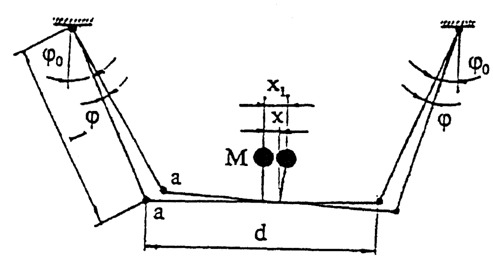


Fig. 1.3.1 Model of the vibrating isolated system for analysis

The generalized coordinate $\varphi$ take as the rope (rod) angula deviation from equilibrium. For small angles $\varphi$ turning angles o both lines are equal. A turning system angle in vertical plane, $\alpha$ is

$$\alpha = \left(\frac{2l}{d}\sin\varphi_0\right)\varphi \qquad (1.3\text{-}2)$$

Where d = Width of the support frame under the isolate system

A horizontal displacement of the center of gravity:
for the frame

$$x = l\varphi\cos\varphi_0 \qquad (1.3\text{-}3)$$

for the whole isolated system

$$x_1 = l\varphi(\cos\varphi_0 + n\sin\varphi_0) \qquad (1.3\text{-}4)$$

Where n = 2h/d
h = Vertical distance between centers of gravity of the system and frame

Horizontal system stiffness relatively of the frame center of gravity can be derived from considering the equilibrium of the joint 'a' (Figure 1.3.1)

$$K = \frac{Q}{l\cos\varphi_0} \qquad (1.3\text{-}5)$$

Where Q = Weight of the isolated system

Graph of the dependency $K = f(\varphi_0)$ is shown on Figure 1.3.2b. Horizontal stiffness relatively of the system center of gravity is

$$K_s = \frac{1}{\gamma^2}K \qquad (1.3\text{-}6)$$

Hence it follows

$$\gamma = \frac{x_1}{x} = \frac{\cos\varphi_0 + n\sin\varphi_0}{\cos\varphi_0} \qquad (1.3\text{-}7)$$

Kinetic energy of the system is

$$K.E. = \frac{I\dot{\alpha}^2}{2} + \frac{M\dot{x}_1^2}{2} \qquad (1.3\text{-}8)$$

Where M = Mass of the isolated system
I = Moment inertia of the isolated system relatively horizontal axis passing across its center of gravity

Substituting expressions (1.3-2) and (1.3-4) into the formula (1.3-8) it can be derived

$$K.E. = \left[\frac{2l^2}{d^2}I\sin^2\varphi_0 + \frac{Ml^2}{2}(\cos\varphi_0 + n\sin\varphi_0)^2\right]\dot{\varphi}^2 \qquad (1.3\text{-}9)$$

Potential energy of the system is

$$P.E. = \frac{Mg}{2}l\cos\varphi_0 x\varphi^2 \qquad (1.3\text{-}10)$$

The natural circular frequency of the system with slope ropes (rods), $\omega_s$, can be derived from formulas (1.3-9) and (1.3-10)

$$\omega_s^2 = \frac{Mgl\cos\varphi_0}{\frac{4l^2}{d^2}I\sin^2\varphi_0 + Ml^2(\cos\varphi_0 + n\sin\varphi_0)^2} \qquad (1.3\text{-}11)$$

Relationship between frequency, $\omega_s$, and slope angle, $\varphi_0$, is exhibited on Fig. 1.3.2a. It can be seen that angle, $\varphi_0$, decreases frequency, $\omega_s$, and in consequence of that enhances the efficiency of suspended vibrating isolation.

In order to determine the dynamic force transmitted to the crusher foundation use Lagrange's equation and present the equation of

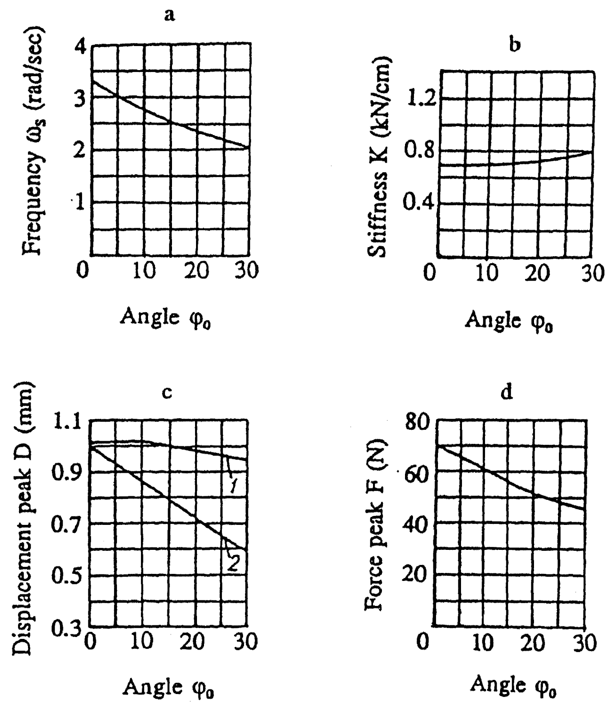


Fig. 1.3.2 Effect of angle $\varphi_0$, on parameters of vibration isolated system
a - Circular natural frequency
b - Horizontal stiffness relatively of the support frame plane
c - Horizontal vibration amplitude (displacement) of the center of gravity: 1 - the isolated system, 2 - the support frame
d - Peak of dynamic force transmitted on structures

motion of the isolated system as follows

$$\frac{d}{dt}\left(\frac{\partial(K.E.)}{\partial\dot{\varphi}}\right) - \frac{\partial(K.E.)}{\partial\varphi} + \frac{\partial(P.E.)}{\partial\varphi} = Q \qquad (1.3\text{-}12)$$

Where Q = Generalized excitation force

$$Q = F\sin\omega t(\cos\varphi_0 + n\sin\varphi_0)l \qquad (1.3\text{-}13)$$

Here F $\sin\omega t$ = Projection of excitation force on the horizontal plane.

Using of formulas (1.3-9), (1.3-10) and (1.3-13) transform equation (1.3-12) to the next expression:

$$\left[\frac{4Il^2}{d^2}\sin^2\varphi_0 + Ml(\cos\varphi_0 + n\sin\varphi_0)^2\right]\ddot{\varphi} + (Mgl\cos\varphi_0)\varphi = Fl(\cos\varphi_0 + \sin\varphi_0)\sin\omega t \qquad (1.3\text{-}14)$$

The solution of the equation (1.3-14) for forced system vibrations is

$$\varphi = C\sin\omega t \qquad (1.3\text{-}15)$$

Where

$$C=\frac{Fl(\cos\varphi_0+n\sin\varphi_0)}{Mgl\cos\varphi_0+4I\omega^2\sin^2\varphi_0-Ml^2\omega^2(\cos\varphi_0+n\sin\varphi_0)^2} \qquad (1.3\text{-}16)$$

Substitute the expression for $\varphi$ in formula (1.3-3) and derive the displacement amplitude of the support frame

$$D_f = \frac{F}{Q}\,\frac{l(\cos\varphi_0 + n\sin\varphi_0)}{1-\left(\dfrac{\omega}{\omega_s}\right)^2} \qquad (1.3\text{-}17)$$

Using analogous way receive the displacement amplitude for the center of gravity of the isolated system:

$$D_{cg} = \frac{P}{Q\cos\varphi_0}\,\frac{l(\cos\varphi_0+n\sin\varphi_0)^2}{1-\left(\dfrac{\omega}{\omega_s}\right)^2} \qquad (1.3\text{-}18)$$

The value of $D_{cg}$ is practically constant for changes of the angle, $\varphi_0$, from 0 to 20 degree (Figure 1.3.2c).

The dynamic force transmitted on the foundation structures is

$$F_{st} = F\,\frac{(1+\tan\varphi_0)}{1-\left(\dfrac{\omega}{\omega_s}\right)^2} \qquad (1.3\text{-}19)$$

The results of calculation show that with growth of the angle, $\varphi_0$ the stiffness of the isolated system relatively to the frame plane increases and the frame displacement amplitude diminishes. The amplitude of frame vibrations decreases faster than the stiffness enhances. Eventually, horizontal force decreases with the growth of the angle, $\varphi_0$ (Figure 1.3.2d).

Horizontal impulse loads excite only isolated system vibrations with its natural frequency. These vibrations are very small.

### 1.3.2 Suspended system with elastic hinges

Real joints, connecting suspended system with structures, are not ideal hinges. Consider the suspended system with elastic pendulum hinges which have the constant angle stiffness, k. The whole system has deflects in the equilibrium from the vertical line on the angle, $\varphi_0$ (Figure 1.3.3).

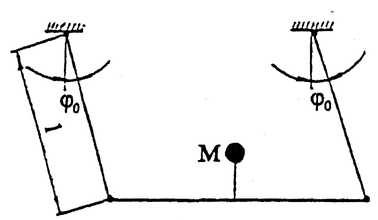


Fig. 1.3.3 Suspended system with elastic pendulum hinges

For determination of the circular natural system frequency, $\omega_0$, it is possible to use the solution received by Bykhovski (1969) for a pendulum:

$$\omega_0 = \sqrt{\frac{Mdl\cos\varphi_0+k}{I}} \qquad (1.3\text{-}20)$$

Final formulas derived in this chapter can be used for monitoring any suspended vibration isolated system.

### 1.4 Foundation under impact machine with a finite pulse duration

A press-drop hammer for compressing and pack of lightweight steel scrap was mounted on the relatively small foundation with foot area of 12.35 $m^2$. The ram mass was 4.2 tonnes.

Foundation vibrations were measured at three points on its top during press-drop hammer operations. Received records showed that the foundation vibrated practically only in vertical direction. For making of one package from lightweight scrap it is necessary a few blows by the falling ram. Energy of the first blow is spending on approach of separate scrap parts. This impact excite relatively weak vibrations (Figure1.4.1a). Next blows complete packing and observed vibrations are analogous with vibrations of forge hammer foundations(Figure1.4.1b).The ram velocity at the moment of the impact was 8.26 m/sec. The maximum amplitude of vertical foundation displacement, $A_f$, reached the value of 1.41 mm, the natural frequency of vertical oscillations, $\lambda$=53 rad/sec, the damping coefficient , b=17.8 rad/sec. Measured vibrations did not interfere with press-drop hammer operations and hammer foundation was in good conditions.

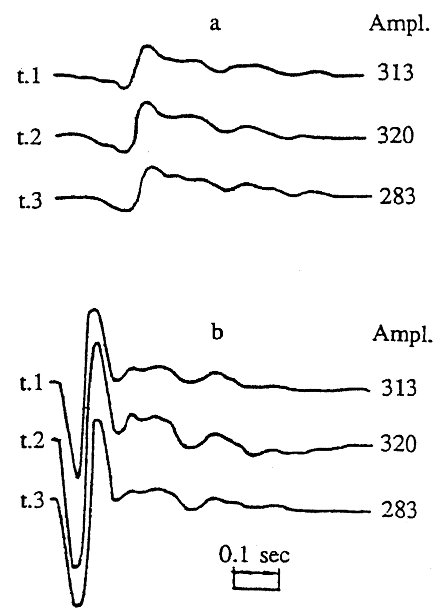


Fig. 1.4.1 Vertical vibration records
a - First blow
b - Third blow

According to dynamic calculation using procedure for forge hammer foundation, the press-drop hammer foundation amplitude was 3 times larger than the measured one. Analysis of experimental results revealed the necessity to take into account the pulse duration. The foundation was considered as the system with one degree of freedom. The rectangular shape pulse was taken for the simplification.

The foundation displacement, excited by pulse with duration $\tau$, can be expressed as follows (Bezukhov and Luzhin, 1963)

$$A_f = A_{st}[\cos\lambda(t-\tau) - \cos\lambda t] \qquad (1.4\text{-}21)$$

$$A_{max} = A_{st}\mu \qquad (1.4\text{-}22)$$

Where $A_{max}$ = Maximum amplitude of vertical foundation displacement
$A_{st}$ = Static foundation displacement under action of the force P
$\mu$ = Dynamic magnification factor

Note a few known dependencies in order to reorganize formula (1.4-22)

$$A_{st} = \frac{P}{Q\lambda^2};\ P = \frac{Q_0 V_0}{\tau};\ \tau = \alpha T;\ \lambda^2 = \frac{AC_z}{Q} \qquad (1.4\text{-}23)$$

Where $Q_0$ = Ram mass, tonnes
$V_o$ = Ram velocity at the moment of impact, m/sec
Q = Total machine and foundation mass, tonnes
A = Foundation foot area, $m^2$
$\xi$ = Ratio of pulse duration to period of natural foundation vibrations
$C_z$ = Coefficient of elastic uniform compression of soil, $kN/m^3$

After performing some transforms, the expression was derived for determination of maximum foundation amplitude:

$$A_{max} = \frac{\mu}{2\pi\xi}\frac{Q_0 V_0}{\sqrt{AC_z Q}} \qquad (1.4\text{-}24)$$

Ratio $\mu/\xi$ is designated as $\beta$, value of which are shown on Figure 1.4.2. For calculation of foundation vibration amplitude, coefficient, $C_z$, was increased three times by analogy with dynamic computing of forge hammer foundations. Finally, formula (1.4-24) can be rewritten as

$$A_{max} = 3\beta\frac{Q_0 V_0}{\sqrt{AC_z Q}} \qquad (1.4\text{-}25)$$

There are the following initial data for calculation $A_{max}$ of the observed foundation under the press-drop hammer: $Q_0$=4.2 tonnes, $V_0$=8.26 m/sec, A=12.35 $m^2$, Q=70 tonnes. Actual soil pressure under the foundation foot is 0.15 MPa. In accordance with Barcan (1962) take $C_z$=30000 $kN/m^3$. Calculation results coefficient $\beta$=6.18 and $A_{max}$=1.0 mm for the pulse duration of $\tau$=0.1 T that actually means an instantaneous pulse. With increasing the pulse duration to $\tau$=0.9 T, coefficient $\beta$=2.22 and

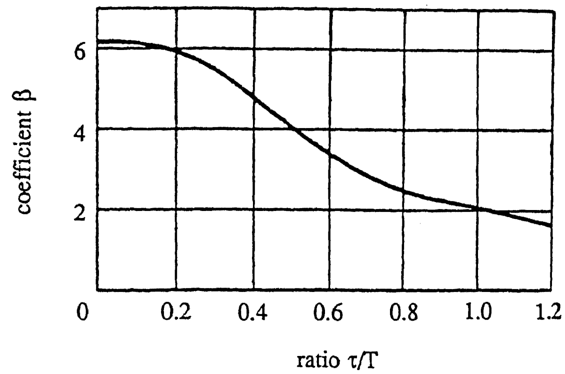


Fig. 1.4.2 Coefficient $\beta$ as a function of ratio of pulse duration, $\tau$, to period, T, of natural foundation vibrations

computed $A_{max}$=1.43 mm that practically coincides with measured one.

Thus, formula (1.4-25) can be used for monitoring the foundation vibrations under press-drop hammer.

## 2 SEISMIC EFFECT OF MAN-MADE VIBRATIONS

All of man-made vibration sources excite elastic waves in soil which may have a harmful effect on structures, sensitive devices and precision equipment, technological processes, and people.

For certain circumstances it is possible to regulate seismic influence of man-made vibrations on surrounding building. One similar case history is considered in this chapter.

Some observations of wave propagation effect from industrial sources are shown in two case histories.

Prediction expecting soil and structure vibrations prior to installation new foundations under machines with dynamic loads are demonstrated in the last case history.

### 2.1 Decreasing the effect of the vibration isolated foundation under forge hammer on the apartment building

Vibrating isolation of forge hammer foundations is used in practice of industrial construction in order to decrease detrimental vibration effect of these foundations on surrounding buildings, processes, people, and other sensitive units. A bearing version of vibrating isolation, consisting from a concrete isolated block and foundation, is widely spreaded. The block together with a hammer is mounted freely on vibroisolators for which steel springs and rubber dashpots are mostly used.

Natural frequencies of vertical block vibrations, $\omega$, usually range from 3 to 6 Hz. It is also known that low frequencies are typical for powerful hammers. The block oscillations transmit to the foundation and induce wave propagation in soil. Commonly, the frequency range from 2 to 5 Hz corresponds the first mode of natural horizontal vibrations of multistory and tall one story buildings. For rather small buildings, frequency values limit from 4 to 10 Hz (Sorokin, 1956). The proximity of source frequencies to ones of natural building oscillations might generate resonance building vibrations. There are similar case histories in practice.

For the elimination of intolerable resonance building vibrations, it is necessary either to reinforce building structures or change the frequency of the concrete block supported by vibroisolators. The first measure is very expensive and can be employed only in the last resort. Change the frequency of vertical block vibrations is much simpler and considerably more economical. In order to rich this goal it ought to decrease the vibroisolator stiffness by elimination a part of them from work. Steel springs are chosen from condition of strength. Therefore it is possible to diminish only dashpot amount. In accordance with this a coefficient of inelastic resistance, $\gamma$, become smaller and an amplitude of block vibrations will bigger.

The quantitative assessment of block vibration parameters after the diminution of dashpot stiffness is shown in the following example. Initial data was taken from Manual (1972): the frequency of natural vertical block vibrations mounted on vibroisolators, $\omega$=4.5 Hz, the total block and hammer mass of 455.1 tonnes, the total vibroisolator stiffness is 3700 kN/cm, the steel spring stiffness of 1560 kN/cm, the rubber dashpot stiffness of 2140 kN/cm, amount of dashpot is 38, the block vibration amplitude, $A_b$, =4 mm (the maximum displacement).

Consider that the decreasing the block natural vertical frequency from 4.5 to 4.0 Hz is sufficient for liquidation the resonance vibrations of nearby situated building. Proceeding from value of $\omega$=4.0 Hz, it is possible to determine parameters of isolated block: the total vibroisolator stiffness is 2940 kN/cm; the stiffness of 26 dashpots is 1380 kN/cm; coefficient, $\gamma$, is equal allowable value of 0.1; $A_b$=4.74 mm that exceed only on 18.5 % initial value of $A_b$=0.4. This example confirm the reasonableness of altering of the isolated system stiffness for the account of turning off some rubber dashpots.

Described above approach was used for the diminish of resonance building vibrations. Five story apartment building was placed on distance approximately 500 m from the vibration isolated foundation under a powerful forge hammer with the mass of falling parts of 16 tonnes (Figure 2.1.1).

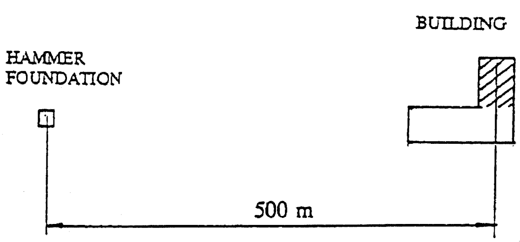


Figure 2.1.1 Layout of apartment building and vibration isolated foundation under large forge hammer
a - Isolated foundation
b - Building

Measured transversal horizontal vibrations of shaded building part were inadmissible when the natural frequency $\omega$ was 3.1 Hz. The decreasing of the frequency $\omega$ to the value of 2.9 Hz for the account of elimination a few dashpots gave a chance to liquidate detrimental vibrations of the apartment building.

Usually buildings have highly narrow resonance zone and as it was demonstrated in the described case history even small changes of the existing frequency results in good profit.

2.2 Soil vibrations induced by horizontal compressors

The substantial dynamic horizontal forces are transmitted from powerful horizontal compressors to their foundations. The exciting primary frequencies are close to frequencies of natural horizontal vibrations of industrial and dwelling building. Because of that in a number of cases intolerable abnormally high vibrations are arisen in the buildings placed nearby powerful compressors.

It is necessary to know propagation waves parameters for determination an acceptable distance between vibration source and sensitive to vibrations receivers. This case history presents the influence of horizontal force direction on field soil vibration distribution.

Vibration source is the horizontal compressor with productivity of 6000 $m^3$/hr. The horizontal unbalanced force is 430 kN with frequency of 125 rpm. The foundation foot area is 200 $m^2$. An underlying stratum is loam with thickness more than 15 m and measured Rayleigh waves spread is 297 m/sec.

Horizontal soil vibrations were measured in four directions: along cylinders, perpendicularly the cylinder axis, along a radius and perpendicularly the radius. It was ascertain from analyzing of acquired data that the first two directions the most completely characterize the amplitude distribution of horizontal soil vibrations around the compressor foundation. Amplitude fields of horizontal and vertical soil vibrations (displacement) are depicted on Figure 2.2.1. As can be seen, amplitudes in the direction along cylinders decrease in all radii approximately uniformly with moving from foundation (Figure 2.2.1a). The amplitude field in perpendicular direction has almost the same distribution, but attenuation enhances 4-10 times. Amplitudes of vertical soil vibrations in the direction along cylinders have the same order as amplitudes of horizontal vibrations in this directions. Vertical soil vibrations attenuate approximately in two times faster in the perpendicular to the cylinder direction.

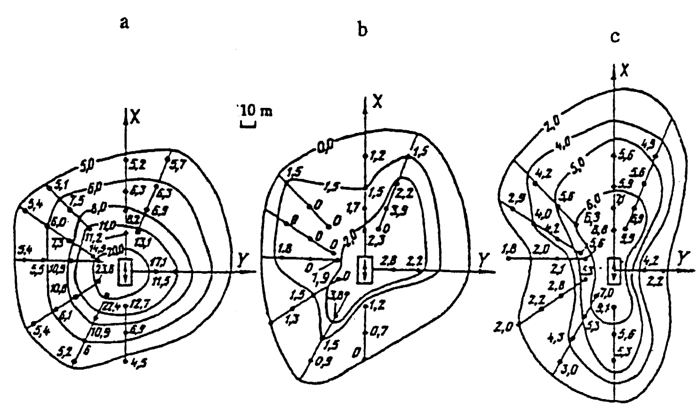


Fig. 2.2.1 Soil amplitude distribution around the foundation under the compressor
a - Horizontal direction along cylinder line (axis X)
b - Horizontal direction perpendicularly cylinder line (axis Y)
c - Vertical direction

Experimental data demonstrates the quantative distribution of amplitude field around the source with the horizontal dynamic force. For other soil conditions and other compressor only absolute amplitude values of soil vibrations will be changed.

Presented actual amplitude distribution gives the possibility of a rational placement of sensitive to vibration equipment at zone closed to the powerful horizontal compressor. In particular, the smallest vertical vibrations of equipment foundations will be for arrangement of these foundations perpendicularly to cylinder axis. Besides that, building with large length compared with wave length is worth while set along a tangent line isolines of horizontal soil vibrations in parallel to cylinder line. This measure provides the same or closed amplitudes of building foundations.

## 2.3 Pile driving nearby a building

Pile driving is a power source of construction vibrations which may harmful affect surrounding buildings, precise equipment, processes and people. The influence of piling operations on surrounding units depends on dynamic parameters of the source, soil conditions, the distance from the source and the sensitivity of structures and equipment to vibrations.

The vibration effect of piling with the impact and vibrating hammers is briefly described in this case history. Piles had to be driven for foundations under new building in close proximity to the existing industrial brick building of five stories. Soil consisted of about 20 m of wet sand. For some reasons, it was very difficult in this case to make the calculation assessment of expecting building vibrations prior to pile driving.

The failure of building structures during piling operations can not commonly occur suddenly. The failure mechanism develops gradually in structural cracks which behavior together with assessment dynamic stress level in structures are a good evidence of expecting damages. Therefore the conclusion about the possibility of piling operations nearby existing building was grounded on the results of study the carrying capacity of some building structures at the time of driving a few testing piles. Measurements of structural vibrations and evaluation the changes of visible cracks in structures were made during pile driving in close distance of 3 m to existing building. Special plaster marks were employed for determination of the smallest enlargements in the crack width. Also, crack lengths were observed.

Received records demonstrated structural vibrations with frequency of 7 Hz. It was a surprise that pile driving with impact hammer induced structural vibrations with the same frequency as a vibratior with low frequency of 420 rpm. Computed additional dynamic stresses in structures were in allowable limits. Analyzing the crack behavior showed that crack length and width did not enlarge during pile driving. No signs of building slow disintegrity were observed. These results were acceptable for implementation of pile driving nearby the existing building.

## 2.4 Prediction irregular foundation settlements and dynamic stresses in structures prior to installation molding machines

For modernization of the steel foundry, eight old molding machines had to be replaced by nine more powerful ones. The plan of one story foundry with placing old and new equipment is presented on Figure 2.4.1. The building cross-section is shown on Figure 2.4.2.

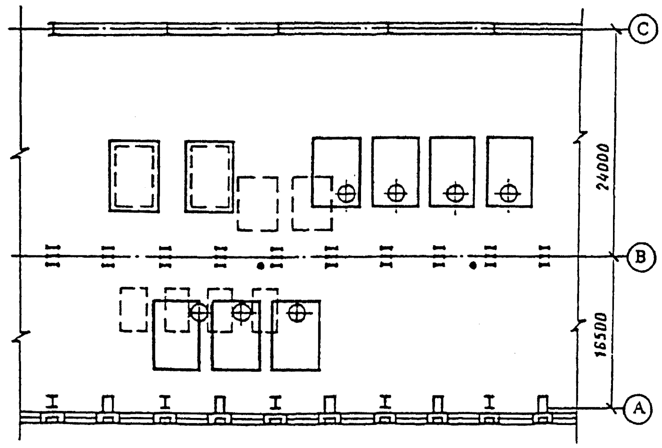


Fig. 2.4.1 Placing of molding machine foundations before (dashed line) and after reconstruction (solid line)
⊕ - Location of impacts on soil

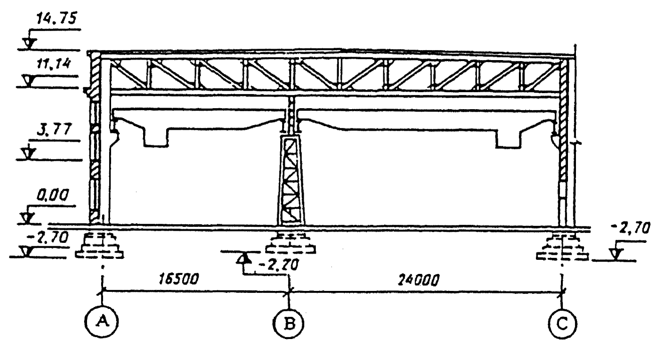


Fig. 2.4.2 Building cross-section

A column spacing on rows A, B, C was 11, 5.5, and 11 respectively. The foundry was equipped by bridge cranes with hoisting capacity of 50-150 kN. The foundry building had steel skeleton-frame and exterior brick walls. Loamy soil was underlain columns foundation with no found water table. The foundry was 25 years old. Vibration effect on building structures from new machines was expected to be bigger. Therefore, certain concerns were arisen about possible dynamic stresses in structures and irregular foundation settlements which might be generated during operation of new molding machines.

Prediction of potential dynamic effect of new machines on soil and structures was performed using method which have reported by Svinkin (1973, 1991). This method has very distinctive practical application since it gives a chance to take into account heterogeneity and multiformity of soil properties and also allows to predict complete vibro-records of soil and buildings with good reliability. These properties are determined with implementation of simple experiments on the particular site where the machine foundation will be installed. Impacts on the soil with definite magnitude are made on the supposed place for installation of new machine foundation. At the time of impact execution on soil, vibrations are measured at the location of interest. Vibration records are the impulse responses of the treated system which experimental determining enable to take into consideration soil and building structures properties. Dynamic loads from the designed machine foundation are regarded as noted. These loads can be derived, for example, from Barcan (1962). Further expected vibrations are computed by using Duhamel's integral.

In the time of experiments in the foundry, impacts on soil were carried out in the locations of each designed molding machine foundation (Figure 2.4.1). For impacts on soil, the ram with weight of 1.0 kN was thrown down from a high of 4-6 m using a bridge crane. Simultaneously, vibrations were measured on column foundations along row B, closed to molding machine foundation, on some column foundations along rows A and C, and also dynamic stresses were determined in truss members and top part of columns at locations with the largest static stresses. Seismographs and strain transducers were employed for measurement foundation vibrations and dynamic structural stresses respectively.

Predicting results were derived for each new machine foundation using referenced procedure. Maximum expecting structural vibrations were found from condition that a half number of molding machines would to work at same time. Obtained data showed 2.4 MPa in the most loading member of the lower truss chord what is only 2 % of design static stresses. Expecting dynamic stresses in top part of columns along row B were less than 4 % of design static stresses.

Nonuniform settlements of column foundations were evaluated by acceleration value of these foundation vibrations. During simultaneous work of new four machines, maximum predicting acceleration did not exceed 108 cm/sec$^2$. The tolerable acceleration value for the site under consideration was found on the basis of measured column foundation vibrations excited by other equipment in the foundry. This is a good practical approach because evaluation criteria for beginning of additional dynamic settlements are highly conditionally. The operation experience of industrial enterprises gives the chance for determination of the acceleration value which can not induced additional settlements of column foundations. This tolerable quantity was 122 cm/sec$^2$. It can be seen the predicting acceleration was less than tolerable one.

Thus, the application of the referenced method allowed to ascertain that predicting dynamic stresses in foundry structures are not dangerous for the building integrity and it ought not to expect nonuniform settlements of column foundations. After new nine molding machines began to work, vibrations of some column foundations and dynamic stresses in individual structures were measured at locations for which prediction of vibrations had been done before. Analyzing predicted and measured records resulted quite satisfactory coincidence of the comparative curves. This confirms the reasonableness and reliability of prediction soil and building vibrations with referenced method.

## CONCLUSION

Described case histories demonstrate the different ways for decreasing abnormally heightened vibrations of machine foundations and surrounding buildings. Analyzing man-made vibrations, grounded on available knowledge about the phenomena of machine foundation vibrations and practical experience, allows to make correct diagnostics of causes induced harmful vibrations and find acceptable solutions of arisen problems.

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